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UNCOVERING UNDERGRADUATE PHYSICS PRE-SERVICE TEACHERS' ERRORS IN ELECTROMAGNETIC INTERACTION AND ELECTROMAGNETIC EFFECTS

Sakyiwaa Boateng, Sizwe J.C. Masuku

Abstract. *Electricity and magnetism are fundamental areas of physics and are integral to science curricula at various educational levels. However, this area has been reported to contain several concepts that students find challenging, leading to perspectives that diverge from scientifically accepted views. This study examines the errors made by physics pre-service teachers (PPSTs) in electromagnetic interaction and electromagnetic effects, using the De Jong and Ferguson-Hessler framework of knowledge types to classify errors into conceptual, procedural, and situational categories. An interpretivist qualitative case study design was employed. The study was conducted with a class of 86 third-year undergraduate PPSTs enrolled in a physical sciences education program. Data were collected using a test designed to assess PPSTs' understanding of key electromagnetic concepts. The test results revealed recurring errors in conceptual understanding and problem-solving techniques, particularly in interpreting electric and magnetic fields, Coulomb's law, and applying Maxwell's equations. Findings suggest that targeted educational interventions focusing on improving students' conceptual and procedural knowledge, along with strategic approaches to problem-solving, could reduce the frequency of these errors. Hence, this study highlights the need for more focused teacher training to address these difficulties related to electricity and magnetism and its long-term impact on physics education.*

Keywords: *conceptual errors, electromagnetic interaction, physics pre-service teachers, procedural errors, physics education*

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Introduction

Conceptual understanding is a crucial objective in education, particularly in science education, as it is essential for grasping phenomena. It entails the construction of meaning, interpretation, and elucidation (Anderson et al., 2001). It entails mastery of the principles that regulate a domain and the interconnections among pieces of knowledge within that domain (Rittle-Johnson et al., 2001). In contrast to conceptual understanding, conceptual misunderstanding encompasses notions that are "incorrect and deficient" (Gurel et a., 2015) and are at odds with scientific knowledge or assertions. These notions may be called alternate conceptions, misconceptions, preconceptions, alternative frameworks or naive ideas (Coştu, et al., 2011). Misunderstandings and misconceptions can be enduring (Sangam & Jesiek, 2012), obstruct learning (Ebenezer et al., 2009), and resist transformation (Turgut et al., 2011) of knowledge, particularly in science education.

In science education, physics is universally recognised as a demanding discipline for both learners and teachers (Çermik, 2020; Liu & Sun, 2021). Electricity and magnetism are important topics in physics that require prior knowledge in mathematics. Electromagnetism is a core component of the undergraduate physics curriculum, typically introduced through sub-units in electricity and magnetism. The sub-units covered include Coulomb's law, electric fields, magnetic fields, Faraday's law of induction, Gauss law and Maxwell's equations. (Griffiths, 2017). These concepts underpin numerous technological advancements and applications, from everyday electronic devices to advanced scientific instrumentation. Enhancing student conceptual understanding and problem-solving skills is a primary objective in courses for physics majors and graduate students, despite using complex mathematics to address problems (Bollen et al., 2018). Mastery of these concepts is essential by assisting students in integrating conceptual and quantitative dimensions of learning to establish a solid knowledge framework of fundamental principles in electricity and magnetism for academic success and practical applications in various fields such as electrical engineering, telecommunications, and medical imaging (Maries et al., 2022). Understanding these laws helps students appreciate the practical implications of electromagnetic theory in

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real-world applications, such as energy generation and transmission (Qin, 2023). Understanding electromagnetic interactions and their resulting effects is fundamental to studying physics and engineering (Alihodžić, et al., 2021).

Despite their importance, students often struggle with mastering these topics, leading to significant errors in comprehension and application (Guisasola, 2014). Research on students' comprehension of electric and magnetic fields at both secondary and undergraduate levels indicates prevalent confusion and alternative conceptions regarding fields and forces, which begin in high school and continue into university (Boateng & Mushayikwa, 2022; Guisasola, 2014; Hoyer & Girwidz, 2024; Zuza et al., 2018). Students encounter challenges in connecting phenomenology, such as observable electromagnetic interactions, with the theoretical frameworks that elucidate these observable changes in terms of fields (Zuza et al., 2018).

Researchers have noted that students equate fields with forces while elucidating unknown electric and magnetic phenomena (Furió & Guisasola, 1998). Many studies have explored students' conceptual difficulties in understanding Gauss's and Ampère's laws, as well as related concepts such as electric flux and magnetic circulation. Common challenges in both contexts encompass the confusion between electric field and flux (Guisasola et al., 2008; Li & Singh, 2018a; Pepper et al., 2012), magnetic field and circulation (Bozzo et al., 2022; Guisasola et al., 2010), the erroneous application of the principle of superposition by presuming that only enclosed field sources produce a field (Guisasola et al., 2008; Li & Singh, 2018b; Pepper et al., 2012), and the inability to identify the requisite symmetry conditions for employing Gauss or Ampere's law to calculate the electric or magnetic field (Li & Singh, 2018b; Wallace & Chasteen, 2010).

Related studies have also shown that students have misconceptions and often make errors ranging from fundamental misunderstandings of vector fields and forces to incorrect applications of mathematical principles (Assem et al., 2024; Mbonyiryivuze et al., 2019). These misconceptions and errors can be attributed to several factors, including the abstract nature of the concepts, the mathematical rigour required, and the often counter-intuitive phenomena described by electromagnetic theory. The concepts' abstractness further compounds the difficulty in understanding electricity and magnetism. Garduza et al. (2023) have pointed out that students often struggle to connect theoretical knowledge with practical applications, particularly in electrostatics, where the relationships between electric fields, forces, and potentials have not been intuitively grasped. This disconnect is echoed by Rahmawati et al. (2023), who have identified the abstract nature of electrical concepts as a significant barrier to student understanding. Hence, the challenge lies in bridging the gap between theoretical constructs and tangible experiences, which is essential for fostering a comprehensive understanding of these topics. For instance, research by Bollen et al. (2016) highlighted that while students could perform calculations, they struggled with the structural understanding of vector operators and applying Maxwell's equations correctly. Similarly, Zuza et al. (2018) found that students faced difficulties linking observable electromagnetic interactions to theoretical explanations, indicating a gap in understanding the underlying principles. These studies collectively underline the importance of identifying and addressing misconceptions and errors in electromagnetism to enhance undergraduate education.

A convergence of these studies indicates that many students do not understand electromagnetism well (Boateng & Mushayikwa, 2022; Bollen et al., 2016; Garduza et al, 2023; Zuza et al., 2018). Most research on students' difficulties with electromagnetism primarily focuses on tertiary-level students and examines more advanced concepts (Hernandez et al., 2023; Suarez et al., 2024). While many studies address general misconceptions in physics, there is a gap in research focusing specifically on physics pre-service teachers (PPST) errors in learning detailed subtopics within electromagnetic interactions and effects, such as Maxwell's equations, Faraday's law, or the nature of electric and magnetic fields in various contexts (e.g., time-varying fields). In addition, research has often generalized student errors across different areas of electricity and magnetism without considering how different contexts (e.g., conceptual vs. problem-solving approaches) influence error patterns. Studies exploring how specific contexts affect error rates are lacking. Hence, there is a need to explore PPST errors and misconceptions at the undergraduate level to understand the errors made by PPSTs in electromagnetic interaction and electromagnetic effects to devise strategies to enhance their learning outcomes in physics education.

Theoretical Framework

Conceptualising Conceptual and Procedural Knowledge in Electricity and Magnetism

In physics education, conceptual knowledge refers to the understanding of fundamental physics principles and the ability to identify and define relevant concepts (Vuola & Nousiainen, 2020). On the other hand, procedural

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knowledge involves the methodological dimension of knowledge, including the procedural nature of experiments and model development necessary to connect physics concepts and laws (Nousiainen, 2012). Research suggests that conceptual and procedural knowledge in physics is interconnected and develops iteratively (Rittle-Johnson et al., 2001). While conceptual knowledge influences procedural knowledge, the reverse relationship is also observed, indicating a bidirectional influence between the two (Rittle-Johnson & Alibali, 1999). This iterative process of development is facilitated by improved problem representation, which aids in bridging the gap between conceptual understanding and procedural skill (Rittle-Johnson et al., 2001). Moreover, the retention of conceptual learning in physics is essential, as demonstrated in studies evaluating students' understanding following interactive physics courses (Wilcox et al., 2020). Active engagement in physics courses, coupled with a focus on conceptual understanding, contributes to long-term knowledge retention. In teaching physics, emphasising conceptual knowledge over mathematical knowledge is recommended to enhance students' understanding (Aprianti, 2023). By focusing on conceptual understanding, teachers can support students in developing deep knowledge of physical phenomena (Carpendale & Cooper, 2021).

Situational knowledge denotes understanding prevalent problem scenarios or contexts within a specific domain, aiding a solver in identifying critical features and articulating the problem effectively. Visualisation construction and other representational methods that support the problem statement effectively reflect situational knowledge (Shavelson et al., 2003).

This study categorises and examines students' conceptual, procedural, and situational knowledge based on the framework proposed by De Jong and Ferguson-Hessler (1996). According to De Jong and Ferguson-Hessler (1996), the quality of knowledge can be evaluated according to its depth, organisation, and interrelations among various knowledge components. High-quality knowledge is distinguished by a coherent structure, facilitating enhanced retrieval and application in problem-solving contexts. In contrast, low-quality information can be disjointed or cursory, resulting in challenges in its application and adaptation to new situations (Fauskanger & Bjuland, 2018). This distinction is crucial in educational contexts, where the objective is to amass information and cultivate a profound comprehension that can be utilised in practical scenarios. The framework's significance transcends theoretical discourse and has practical ramifications for curriculum development and teaching methodologies. Teachers are urged to cultivate learning settings that promote the advancement of all three categories of knowledge. This can be accomplished using diverse instructional methods, such as problem-based learning, which challenges students to confront real-world issues necessitating the amalgamation of conceptual, procedural, and conditional knowledge as suggested by Bruns et al. (2021).

Literature Review

Students' Common Errors and Misconceptions in Electricity and Magnetism Concepts

Misconceptions, also called common errors, are incorrect understandings or flawed interpretations of concepts, often deeply rooted in learners' cognitive frameworks (Smith et al., 1994). In physics education, misconceptions are particularly significant as they tend to be robust and resistant to change, even after teaching (Chi, 2005; Disessa, 1988). Misconceptions in physics are often formed from everyday experiences or prior knowledge that conflicts with scientific principles (Hammer, 1996). Chi (2013) has described misconceptions as alternative frameworks that learners construct, often influenced by their pre-existing mental models. In electromagnetism, for example, students might incorrectly assume that electric current flows as if it is water, which is flowing in pipes, or electric and magnetic fields are similar to tangible physical objects.

According to Duit (2014), misconceptions in physics can be classified into several categories: preconceptions (ideas formed before formal instruction), flawed mental models (simplified or incorrect internal representations of phenomena), and intuitive reasoning errors (incorrect extrapolations from everyday experiences). These misconceptions tend to persist because they provide students with seemingly logical explanations for observed phenomena, even if those explanations conflict with scientific principles.

Nevertheless, a conceptual error refers to a misunderstanding of a concept that does not align with the scientific definition commonly accepted by experts in the relevant field. One standard conceptual error relates to understanding electromagnetic fields and their effects. Students may incorrectly interpret the behaviour of electromagnetic field lines, leading to misconceptions about the direction and magnitude of forces exerted by these fields (Dori & Belcher, 2005). Moreover, misconceptions about the nature of electromagnetic fields in matter compared to vacuum can complicate students' visualization and comprehension of electromagnetic interactions

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(Choi & Yun, 2019). A lack of comprehension of the problem's concepts or a misunderstanding of the link between the problem's concepts are both examples of conceptual mistakes. For example, pre-service teachers misinterpreting Gauss's Law for electric fields (which relates the electric flux through a closed surface to the charge enclosed) can cause errors in calculating electric fields for various charge distributions.

A procedural error refers to errors in the process of executing algorithmic procedures, which include operations, algorithms, placements, and incorrect steps, as well as missing steps in problem-solving (Herholdt & Sapire, 2014; Siyepu, 2013). Procedural error may be due to mis-generalisation, where students generalise an existing concept wrongly (Andriani & Nurhasanah, 2021). Furthermore, procedural errors occur when students correctly understand the fundamental concepts and theories but make mistakes in applying them to solve problems. One possible source of procedural errors in electromagnetism is the misapplication of fundamental concepts such as electric and magnetic fields, charges, and currents. For instance, calculating electromagnetic forces or fields could lead to inaccuracies in predicting the behaviour of charged particles or magnetic materials.

Several studies have documented common errors in students' understanding of electromagnetic concepts (Lattery, 2016; Leniz et al., 2017; Maloney et al., 2021). For instance, Lattery (2016) identified common errors in Faraday's Law and Lenz's Law, where students often believe that a change in magnetic flux directly creates current without recognizing the induced electric field. Duit and Treagust (2012) also highlighted that students frequently misinterpret induced current direction, assuming it flows in the same direction as the external magnetic field instead of opposing the change in flux. Similarly, Maloney et al. (2021) noted that students frequently confuse the concepts of electric potential and electric field, incorrectly assuming they are the same or have identical effects on charged particles. This stems from an inappropriate analogy and a misunderstanding of charge conservation in electric circuits, as Leniz et al. (2017) noted in their study. A frequent error involves conflating electric potential with electric field strength, leading students to assume incorrectly that the two are directly proportional, regardless of the spatial configuration of the charges. Students often confuse electric potential with electric field strength, resulting in misunderstandings regarding their interaction in a circuit. Studies reveal that students frequently do not comprehend that electric potential is a scalar variable affecting charge flow in an electric field, as Leniz et al. (2017) noted.

In magnetism, students often possess incorrect notions about magnetic fields and forces. One common misconception is that magnetic field lines represent physical entities that can be "seen" or that their density directly indicates magnetic strength. Moreover, students struggle to understand that magnetic forces act at a distance, leading to incorrect interpretations of how magnetic fields interact with moving charges or currents. A study by Maloney et al. (2021) shows that many university students incorrectly believe that a magnetic field can exert force on a stationary charged particle. This misconception arises from confusion between electric and magnetic forces, with students failing to recognize that the magnetic force acts only on moving charges. These conceptual errors are compounded when students try to apply the right-hand rule, often confusing the direction of the magnetic force and current flow (Heckler & Sayre, 2010).

Electromagnetic interactions present an additional layer of complexity, as students must integrate their understanding of both electric and magnetic fields. Many students mistakenly believe that a magnetic field alone can induce current without changing the magnetic flux (Mulhall et al., 2001). Maloney (1985) conducted a study assessing students' understanding of magnetic poles following instruction in a general physics course. The findings indicated that most students held an alternative conception, believing that magnetic poles are charged, which indicates a significant issue is students' challenges in visualising electric and magnetic fields. In a similar study, Malgieri et al. (2021) found that students often struggle to accurately draw field lines for magnets, indicating a fundamental misunderstanding of how magnetic fields operate. This difficulty is echoed by Gülçiçek and Damlı (2018), who highlight that students' representations of magnetism as magnetic poles or field lines can lead to confusion when solving problems related to force. The inability to visualize these concepts can significantly impede students' problem-solving abilities in electricity and magnetism.

The question is, how do we prepare pre-service teachers to teach physics effectively and with understanding? Studies have shown that inquiry-based learning encourages students to engage actively with scientific concepts through questioning, investigation, and problem-solving (Listiono et al., 2025; Safkolam et al., 2024; Sapriati et al., 2024). Sapriati et al (2024) emphasised that inquiry has become synonymous with effective science learning, particularly biology. This suggests that teacher education programs must integrate inquiry skills into their curricula to foster a deeper understanding of scientific principles among pre-service teachers. Experiential learning (Ng et al.,.2019; Pherson-Geyser et al., 2020), which emphasizes learning through experience and reflection, is another effective pedagogical approach for preparing pre-service teachers in physics. This method allows pre-service

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teachers to engage in hands-on activities that mirror real-world scientific practices. This suggests that experiential learning opportunities should be a core component of teacher education programs, enabling pre-service teachers to develop practical skills in teaching physics.

Research Aim and Research Questions

This study examines PPSTs' common errors in understanding and applying physics concepts during problem-solving.

The following research questions guided the study:

1. What are the common cognitive errors and misconceptions PPSTs exhibit in understanding electromagnetic interactions and effects, as identified through science knowledge classification analysis?
2. What specific stages of science knowledge classification (situational, conceptual, procedural) do PPSTs struggle with the most when learning about electromagnetic interactions and effects, and what are the contributing factors?

Research Methodology

General Background

This study adopts an interpretivist qualitative case study approach to uncover and understand third-year PPSTs' errors in electromagnetic interactions and their effects. The interpretivist paradigm is suitable for this research as it aims to explore students' subjective experiences and conceptual understanding, recognizing that knowledge is constructed through social and individual interpretation (Creswell, 2013). The case study design (Yin, 2018) was employed to facilitate a comprehensive dataset that encapsulates diverse experiences and insights inside a singular educational environment. Yin (2018) has highlighted the significance of context in case study research, especially pertinent when analysing the learning environment of these PPSTs. This implies that the study deeply explores how the specific learning environment, instructional methods, and prior knowledge shape PPSTs' misconceptions and problem-solving approaches. A case study allows for an in-depth, situated understanding of these errors, considering real classroom interactions, assessment practices, and educational interventions. This approach helps develop targeted strategies to address conceptual and procedural difficulties, ultimately improving teacher preparation and physics education quality.

Sample

The participants included a whole third-year physics class of 86 PPSTs registered for the Physics III course in a 4-year Bachelor of Education degree programme in a university in the Eastern Cape region of South Africa. The study employed a whole-class sampling approach, meaning all 86 PPSTs in the cohort participated (47 males, 55%; 39 females, 45%). This decision was made to ensure inclusivity and representativeness within the course. While the study provides meaningful insights into the targeted group of PPSTs, generalizability beyond this cohort could be considered within the context of similar teacher education programs, as the study aims for transferability, where insights can inform broader discussions in teacher education. No formal sample size calculation was necessary since the study involved the entire available cohort. The decision to include all students was based on accessibility and the practical advantage of working with a whole group rather than a subset.

The average age of the participants was 21 years. All participants majored in physics and chemistry as their primary subjects. Mathematics was their third major subject. For anonymity, the participants were randomly coded as PPST1, PPST2, and so on up to PPST86. Before data collection, ethical approval for the study was obtained from the Faculty of Education Ethics Research Committee (with protocol number FEDSRECC014-03-23). Participation was voluntary, and informed consent was secured from all participants. Confidentiality and anonymity were maintained by de-identifying responses and ensuring no participant could be linked to specific data. In addition, participants were informed of their right to withdraw from the study at any stage without any consequences.

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The Physics Course Design for a 4-Year B.Ed. Education Programme

The Physics course in this study context was designed to equip pre-service teachers with advanced content knowledge in Physics, enabling them to teach and inspire future learners effectively. The program builds a strong foundation in classical and modern physics, progressing through theoretical and applied aspects to develop deep conceptual understanding and practical teaching strategies.

The first-year Physics I course introduces fundamental concepts in classical and modern physics, emphasizing conceptual clarity and foundational problem-solving skills on the following topics: Classical Mechanics, General Optics, Electricity and magnetism, Current Electricity, Atoms and Kinetic Theory, The Quantum Atomic Theory.

The second-year Physics II course extends the foundational knowledge into more complex topics, covering multi-dimensional motion and quantum aspects of light (Classical Mechanics 2, Thermodynamics, Gas Laws, The Quantum Theory of Light, Modern Physics, Nuclear Physics, The Particle Nature of Photons).

The third-year Physics III course delves into advanced theoretical physics, solid-state, and electromagnetism, preparing students for research and innovative teaching methods (Quantum Mechanics, Statistical Mechanics, Solid State Physics, Modern Physics, Electromagnetism).

The fourth year focuses on practical teaching experience, curriculum development, and research in physics education. This structured curriculum allows pre-service teachers to gain content mastery and develop effective pedagogical approaches to teaching Physics in secondary education, ensuring that pre-service teachers graduate as well-rounded physics teachers capable of teaching, innovating, and researching physics education.

The mode of delivery for this course is a blended learning approach, combining face-to-face lectures, laboratory practicals, interactive tutorials, and digital learning tools to enhance conceptual understanding, using the ideas as framed by Novotná and Demkanin (2024), on the typology of teachers to categorise their approaches and perspectives on teaching physics. By developing this typology, the framework provides insights into variations in teaching styles, instructional decision-making, and how educators address students' learning challenges.

Instrument and Procedures

The study was undertaken in one unit of Physics III (Electricity and Magnetism) following the completion of the unit. The justification for choosing Electricity and Magnetism was that, the unit is a conceptually demanding topic in physics education, often associated with high cognitive load and abstract reasoning. Investigating its impact on preservice teachers' understanding provided valuable insights into their learning processes.

A unit test was administered to the PPSTs, conducted as a supervised test lasting two hours. Conducting the study after the completion of the unit ensured that participants had full exposure to the content and instructional approach before their learning experiences were assessed. This allowed for a more comprehensive evaluation of their conceptual understanding. Data collection after unit completion allowed PPSTs to reflect holistically on their learning experiences and any conceptual challenges they faced. Capturing these reflections, post-instruction provided richer qualitative and quantitative data.

A marking rubric was created and overseen by a subject matter expert, and it was utilized to grade the test. Once the test was scored, the study team assessed each PPST response. A second marker was used to mark the scripts to ensure consistency. A level of agreement of over 95% was attained between the two markers. After finishing the marking process, the PPSTs' responses to the unit test were analysed.

Multiple measures were taken to ensure the validity and reliability of the unit test. Content validity was established by aligning the test items with the learning objectives and key concepts covered in the unit. This ensured that questions adequately represented theoretical and practical aspects of electricity and magnetism. Construct validity was verified through expert reviews by physics specialists, who confirmed that the test accurately measured conceptual understanding and problem-solving skills. The test underwent a pilot study with a small group of PPSTs to enhance reliability to identify ambiguous questions and refine item clarity. Inter-rater reliability was maintained using a standardized rubric for scoring. These measures collectively ensured that the test produced stable and accurate assessments of the PPSTs' understanding of electricity and magnetism.

Data Analysis

In analysing the responses, the researchers did not employ scale scores to assess each PPST's knowledge level. The process of problem analysis required significantly more effort than grading itself. This was because the

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researchers were not concerned with simply determining whether the quantitative solutions were right or wrong. Instead, the researchers focused on identifying the specific errors made by PPSTs and characterizing them to gain insights into their potential learning difficulties when they learn electricity and magnetism.

The researchers employed the framework established by Miles and Huberman (1994) for analysis. This methodology consists of three sequential phases: data reduction, data display, and conclusion drawing and verification. In the data reduction phase, the written responses of each PPST to each question were analysed, and the correct and incorrect responses (errors) were classified using De Jong and Fergusson-Hessler›s (1996) framework of knowledge kinds.

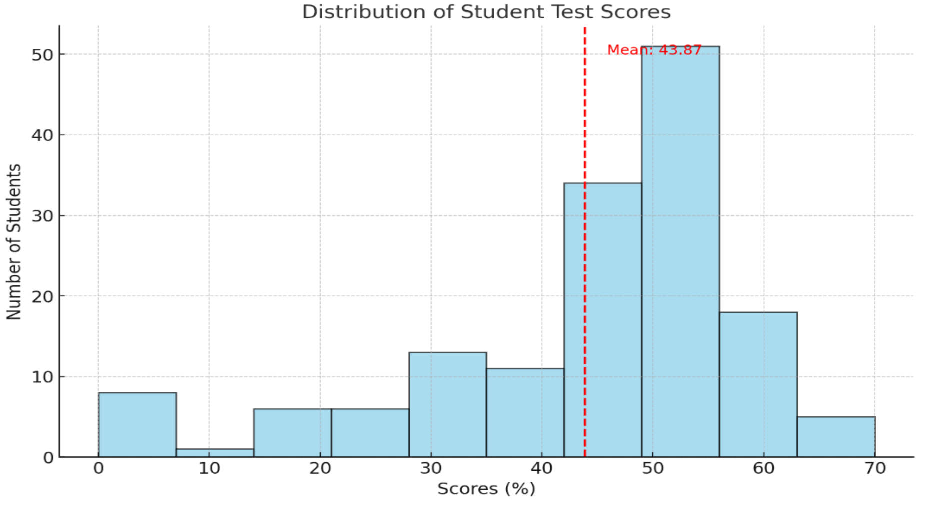
Situational, conceptual, and procedural errors were employed to correlate to the distinct types of knowledge in order to categorize students' errors. Using the analysis and classification method, the researchers classified and documented all errors associated with each test question on a spreadsheet. These errors were subsequently consolidated into a comprehensive test analysis report. This approach ensures a robust analysis of the PPSTs' errors.

Research Results

PPSTs Distribution of Test Scores

The maximum total score for the test was 50 marks (100%), with each item assigned five marks. The analysis indicated that PPSTs' marks varied from 0 marks (0%) to 35 marks (70%), with 0% representing the minimum and 70% the maximum score. The mean score was approximately 43.87, with a standard deviation of 15.32. The distribution of PPST test results, as illustrated in Figure 1, reveals significant variability, highlighting that while some PPSTs performed well, a considerable number fell into lower performance categories.

Figure 1
Distribution of PPSTs Test Scores



Errors in Determining Electrostatics Force Acting on an Expanded Segment

In question 1.1.1, PPSTs had to determine the electrostatic force acting on an expanded segment of a rod aligned along the *z*-axis, with the point of thermal expansion initiation at the origin. The scenario was that a positive charge magnitude +Q was located along the *y*-axis, positioned 1 meter away from the rod. About 90% of PPSTs answered this question wrongly. Figures 2 (a) and (b) show typical PPSTs responses to these questions.

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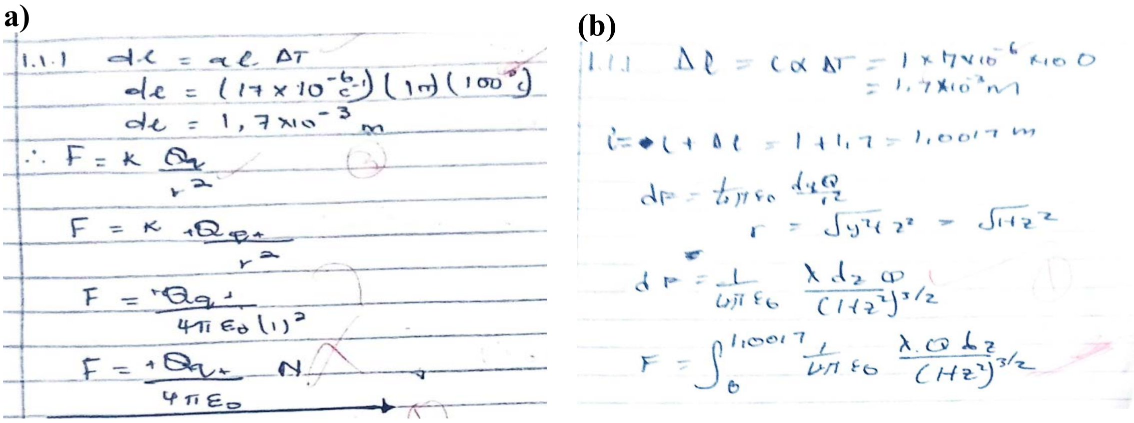
Figure 2
PPSTs Responses



The identified inaccuracy concerns epistemological and practical errors in applying Coulomb's Law. The PPST9 correctly calculated the thermal expansion of the rod (Figure 2a). However, PPST9 incorrectly used Coulomb's Law to determine the electrostatic force. This is a conceptual error since PPST9 specifically neglected the force's vector nature and failed to adjust for the expansion influencing the distances between charges adequately. PPST23 made a similar conceptual error (Figure 2b) due to a misunderstanding of the spatial encoding of machinery after expansion. In this question, PPSTs were to indicate that the force fluctuates due to the charges in the y-direction; the contained charges should have been integrated throughout the extended region; however, the PPSTs treated them as point charges. This indicates a profound conceptual knowledge difficulty. Hence, PPSTs struggled to transition from a more straightforward point charge model to a distributed charge system that employs line charge densities and calculus for integral evaluation. This finding highlights procedural and situational errors in the PPSTs' understanding of electricity and magnetism, specifically when transitioning from point charges to distributed systems. Here, the PPSTs treated the charges as point charges rather than recognizing them as distributed over a region. This reflects a failure to follow the correct procedural steps for analysing distributed charge systems, which involve integrating line charge densities over the given spatial region. The lack of integration for the extended distribution of charges suggests that PPSTs struggled to apply calculus-based techniques, which are essential for solving problems involving continuous charge systems.

Furthermore, PPSTs fail to adjust their mental models to the problem's context. While point charges are appropriate in more straightforward, isolated cases, the given situation requires an understanding of a more complex system where charges are spread across a line or region. This inability to shift from a point charge model to a distributed charge model reveals their conceptual limitations in interpreting the situation correctly.

The findings, therefore, expose a procedural error (failure to apply correct mathematical tools) and a situational error (failure to adapt to the problem's demands). This highlights the need for instructional interventions to strengthen PPSTs' conceptual and procedural knowledge of distributed charge systems in electricity and magnetism.

Errors on Electric Field Strength on the Rod

Question 1.1.2 of the test was a continuation of 1.1.1. where PPSTs were asked to determine the electric field strength on the entire rod while experiencing thermal expansion (at a temperature approximately one-third above the room temperature) pivoted at the origin along the *z*-axis, with the positive test charge placed as in question. Most PPSTs did not answer this question. Figures 3 (a) and (b) show typical PPST responses to this question.

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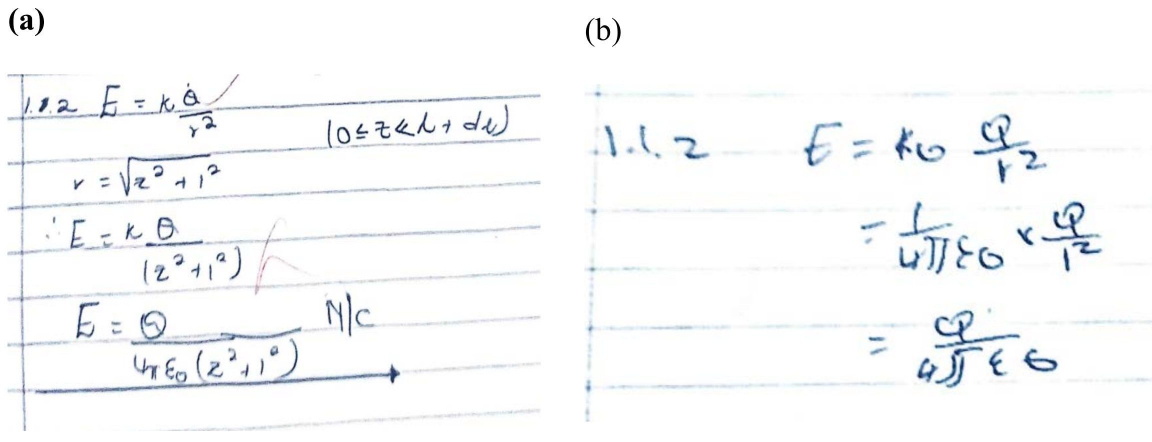
Figure 3
PPSTs Typical Responses



In this case, the error stems from the incomplete application of electric field integration to a continuous charge distribution. In Figure 3, PPST56 (a) and PPST 12 (b) attempted to apply the basic electric field formula, but they failed to convert the continuous charge spread along the expanded rod into a point charge. The actual error does not lie in the shift from a discrete to a continuous charge distribution, as this is a conceptual error. Another aspect is determining the electric field strength for a charged rod, which requires integration over the rod's length (a and b).

This led to the PPSTs underestimating the exact strength of the field by systematically ignoring the contributions of every small charge element. This highlights a more complex challenge: How, for instance, do the electric fields of various sources superpose, particularly when continuous functions describe functions? A procedural error arises from incorrectly executing the mathematical steps required to determine the electric field through integration. Even if PPSTs conceptually understood that integration is needed, they failed to systematically account for the contributions of all small charge elements along the rod. This suggests a flaw in applying the correct integration steps over the rod and the length of the rod. Situational errors occurred when PPSTs failed to adapt their knowledge to the specific conditions of the problem (Figures: 3a and 3b). In this case, the rod's expanded length and distributed charge created a situation where the PPSTs needed to adapt their understanding and problem-solving strategy. This indicates an inability to appropriately modify their reasoning based on the unique setup of the problem, leading to situational error.

The findings reveal a conceptual error in understanding continuous charge distributions, a procedural error in executing the necessary integration steps, and a situational error in adapting their approach to a specific problem involving a charged rod.

Errors in Electric Potential at a Point Above a Ring

In question 1.2.1., PPSTs were asked to deduce the strength of the electric potential recorded by the electrostatic field meter containing a test charge at *h* meters above the *xy* plane as the Cu rode in question 1.1. was bent using a rod bender without discharging the rod, a ring with the total length of *l* + *dl* was formed since this happens at a temperature one-third above room temperature. An electrostatic field meter containing a test charge is positioned *h* meters (along the *z*-axis) above the ring's centre, which is in the x, y plane. This is at room temperature (stress and strains are neglected). This was also a question that most PPSTs failed to answer. Figures 4 (a) and (b) show typical students' responses to this question.

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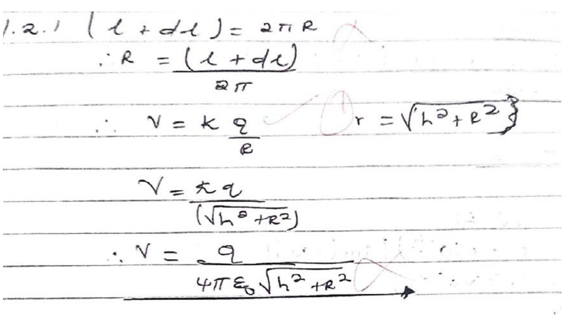
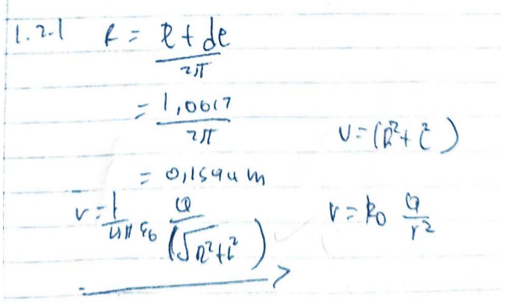
Figure 4
PPSTs Typical Responses on Electric Potential

(a)



(b)



The symmetry and distance relation we use to define it give rise to this phenomenon. The PPST33 (Figure 4a) attempted to apply the potential formula for a point charge, unaware that the situation involved a ring of charges. PPST9 (Figure 4b) made an error in determining the effective distance of the test charge and the ring, leading to incorrect responses. The genesis of this mistake is not seeing the mirror image of the ring-charge configuration. Assuming symmetry greatly simplifies the problem, but it also leads to incorrect assumptions about distance and potential measurement location. Determining when to apply symmetry and when not is a greater challenge, as most PPSTs tend to overcomplicate the function by applying symmetry, making their integration more complex than necessary. This is a conceptual error because the PPSTs (PPST33 and PPST9) assumed symmetry where it may not apply, leading to incorrect assumptions about the effective distance and potential measurement location. While symmetry can simplify specific problems, misapplying it demonstrates a failure to conceptualise when and how symmetry is valid. The inability to visualize the mirror image of the ring-charge configuration also suggests a lack of conceptual understanding of spatial relationships in electric fields. Conceptual understanding of the electric field or potential due to continuous charge distributions involves integrating contributions from individual charge elements. An error about the effective distance or field point indicates a lack of understanding of how distances are defined and used in Coulomb's Law. In addition, PPST33 and PPST9 struggled with choosing when and how to use symmetry, which indicates a procedural error in their problem-solving strategy.

Common Errors Related to Magnetism

The sub-unit on electricity and magnetism typically covers a range of advanced concepts that build on fundamental electromagnetism learned in earlier years. The test covered concepts such as Magnetic Fields and Forces, Electromagnetic Induction, Magnetic Materials, Maxwell's Equations, and Electromagnetic Waves.

Errors in Magnetic Force on Wire Segments

In question 2.1, PPSTs were tasked with calculating the total magnetic force exerted on specific wire segments, based on a diagram depicting a straight conductor segment of length L orientated perpendicularly to the plane on the right, with the current flowing in opposition to the magnetic field B, succeeded by a semicircular segment with a radius of $R = 2$ m and an additional straight segment of length $L = 2$ m. The conductor transmits a current of $I = 2$A. The magnetic field $B = 2$ T is homogeneous and orthogonal to the plane of the diagram, orientated outward from the plane. Figures 5 (a) and (b) show typical responses to this question by PPSTs.

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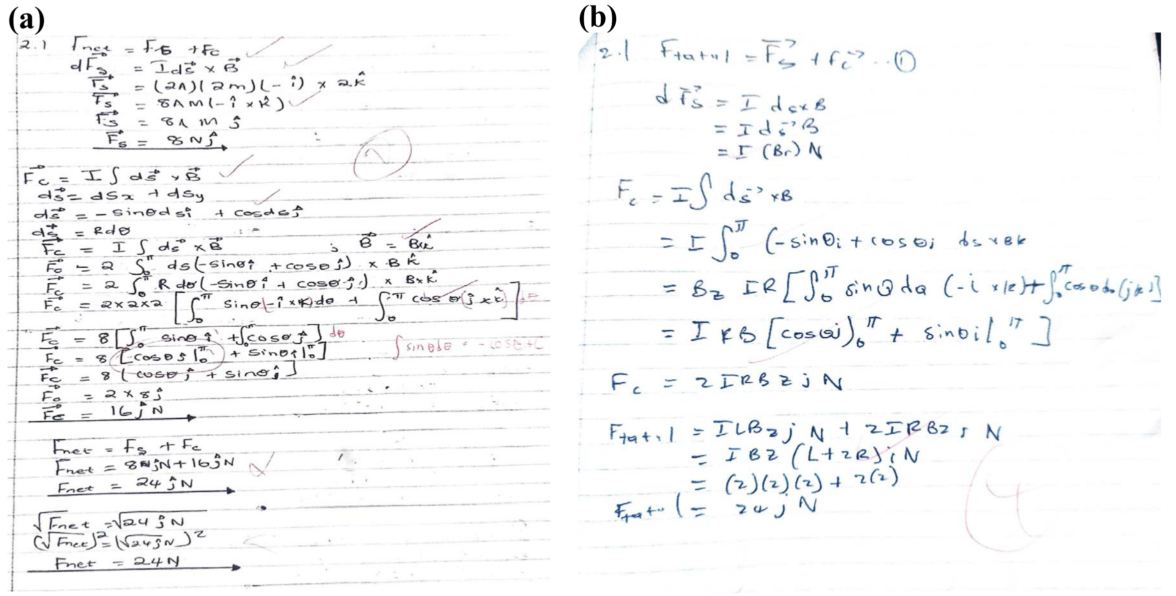
Figure 5

PPSTs' Typical Responses to Magnetic Force on Wire Segments



PPST75 response for Figure 5a was accurate. However, PPST75 did not complete the task due to conceptual difficulties. PPST75's failure to complete the task in Figure 5a points to conceptual difficulties. That was the case with most PPSTs who partially answered this question. Specifically, the inability to properly account for the curved segments indicates that PPSTs do not fully understand how magnetic force behaves on curved paths. This suggests a misunderstanding of how the magnetic force, as derived from the Lorentz force law applies when the geometry of the current-carrying conductor changes.

The lack of application of the Biot-Savart Law also reveals a conceptual gap regarding magnetic force distribution over a curved segment. PPST2 error in Figure 5b pertains to inaccurate force estimates when considering curved segments. Regarding the answers to the questions, it was evident that several of the highest-scoring PPSTs obtained a numerical value for the magnetic force on the straight segments but failed to integrate properly over the length of the semicircular segment. The right way would have been to apply the Biot-Savart Law or integrate the Lorentz force through the arc. The error arises from the assumption that the magnetic force on a curved conductor segment is identical to that on a straight segment. Since the force acting on the curve changes along it.

While PPSTs correctly obtained numerical values for the magnetic force on the straight segments, they failed to integrate appropriately over the semicircular segment. This reveals that PPSTs know how to compute forces for simple, linear segments but struggle with the procedural aspect of applying integration techniques to non-linear geometries. PPSTs did not recognize that the force on a curved segment requires integrating the force contributions along the arc using the Lorentz force or Biot-Savart Law. This procedural error is often linked to insufficient practice with problems that involve curved geometries and continuous distributions.

Error on Ampere's Law for a Long Wire

In question 2.2, Amperian loops of a long straight wire of radius *R* carrying a current *I* of uniform current density were shown to PPSTs. PPSTs were asked to use Ampere's law to find the magnetic field strength outside and inside the wire. Figure 6: (a) – (b) shows the typical responses of PPSTs based on this question.

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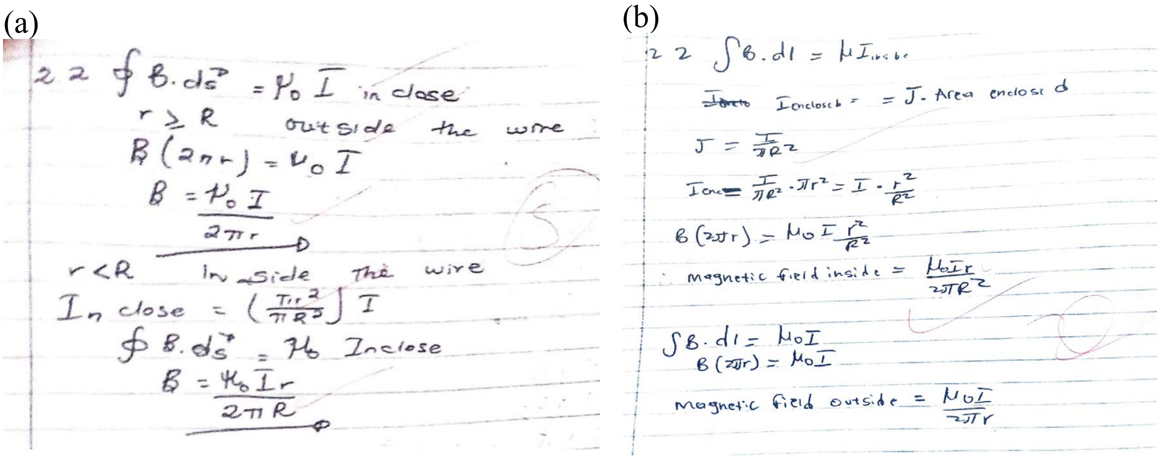
Figure 6
Ampere's Law for a Long Wire



PPST39 in Figure 6a managed to compute the values into the equation to arrive at the correct answer. However, PPST12 response in Figure 6b, indicates an incorrect configuration of Ampere's loop for both the regions inside and outside the wire shield. A conceptual error occurs when PPST12's incorrect configuration of Ampere's loop indicates a misunderstanding of how Ampere's Law operates in different regions (inside and outside the wire shield). This reveals a conceptual gap in relating current distributions to magnetic fields.

Furthermore, PPST12's failure to configure Ampere's loop correctly and differentiate between the regions inside and outside the wire points to a procedural flaw. While PPST12 might understand that Ampere's Law is used to compute magnetic fields, he misapplied the procedure for defining the loop or integrating the enclosed current, particularly when it depends on radial distance. PPST12 overlooked the detail because he was accustomed to external enclosures with uniform or straightforward currents. Of course, most PPSTs overlook this because they solely focus on understanding external enclosures.

Error on Magnetic Force on Wire in a Multi-wire Setup

In question 2.3, PPSTs were given four long straight wires which were located at the corners of a square of an area 4 cm^2. All the wires carry equal currents of 15A. Currents in the wires A and B are inwards, and C and D are outwards. PPSTs were required to determine the total magnetic force per unit length at the wire. Figure 7: (a) – (b) shows the typical responses of PPSTs based on this question.

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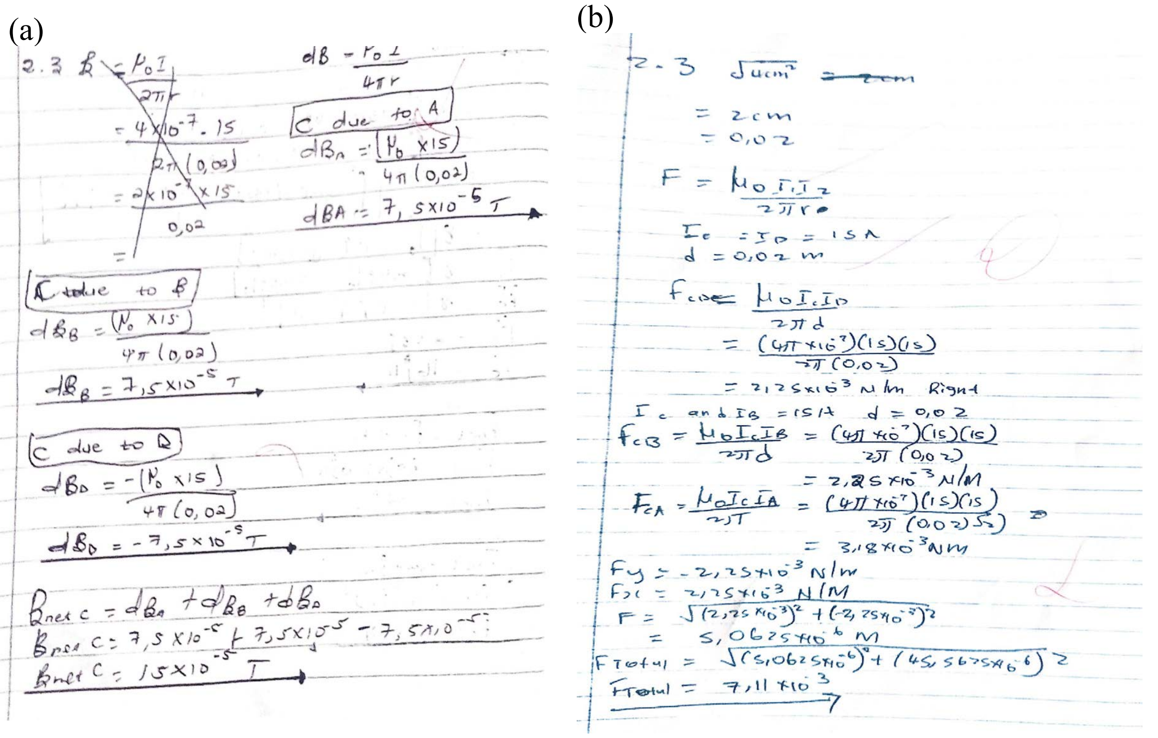
Figure 7

PPSTs Responses of Magnetic Force on Wire in a Multi-wire Setup



In this scenario, PPSTs were supposed to apply the superposition principle and vector addition of forces in solving this problem. However, the application of these principles is normally a major issue in many physics problem-solving questions. Despite PPST52 response in Figure 7b determining the correct direction of the currents, PPST52 calculated the total magnetic force incorrectly due to a misunderstanding of how forces act when more than two wires are involved. Once again, the PPST52 failed to properly account for the vector nature of the forces, leading to incorrect values resulting to a procedural difficulty in vector arithmetic. The primary issue arises when PPSTs attempt to add vectors, particularly when the forces do not form a simple rectangular shape, as shown by the PPST3 response in Figure 7a, which indicates an incomplete conceptual understanding of vector addition.

Discussion

This study examines the persistent conceptual, procedural and situational error and problem-solving challenges encountered by PPSTs in electromagnetic interactions and electromagnetic effects, emphasizing their understanding of key principles such as Ampere's and Gauss's laws, vector analysis and the superposition principle while proposing interventions to enhance their preparedness for teaching practices.

The study's findings reveal significant conceptual challenges PPSTs face in mathematical problem-solving, particularly in mastering content related to electrostatics. Many PPSTs demonstrated conceptual and procedural difficulties in grasping Coulomb's Law's foundational principles and applications. These challenges, including misinterpretations of the law's theoretical underpinnings and algorithmic missteps, are key areas where interventions can enhance PPSTs' preparedness for teaching practice. One notable example involved PPST9, which accurately calculated the thermal expansion of a rod but incorrectly applied Coulomb's Law to determine the electrostatic force. This error highlights students' challenges in correctly executing algorithmic procedures and avoiding misgeneralizations, which occur when existing concepts are misapplied to new contexts (Andriani & Nurhasanah, 2021). These findings align with prior research identifying widespread confusion and persistent alternative conceptions of electric and magnetic fields among secondary and undergraduate students (Guisasola, 2014; Hoyer & Girwidz, 2024; Zuza et al., 2018). Previous studies have indicated that misconceptions, including those related to the direc-

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tion and magnitude of forces exerted by electromagnetic fields, often originate at the high school level and remain unresolved through higher education (Dori & Belcher, 2005). Students frequently fail to recognize symmetry conditions critical for effectively using these laws (Wallace & Chasteen, 2010). As suggested by Zuza et al. (2018), there is a critical and urgent need for targeted interventions to address conceptual and procedural errors, particularly in connecting observable electromagnetic phenomena with their theoretical explanations.

In the literature, the difficulty that PPSTs face in transitioning from a more straightforward point charge model to a more complex distributed charge system, which requires the application of line charge densities and calculus-based integral evaluations, has been well-documented(Bozzo et al., 2022; Guisasola et al., 2010). This challenge highlights significant procedural and situational errors in their understanding of electricity and magnetism. This study showed that PPSTs often treat charges as point entities, failing to recognize them as distributed across a spatial region. Such misinterpretations reflect a need for more adherence to correct procedural steps, which involve integrating line charge densities over the relevant spatial dimensions (Herholdt & Sapire, 2014; Siyepu, 2013).

The procedural errors observed align with the broader category of algorithmic execution failures, encompassing incorrect operations, algorithm misapplications, and omissions of critical problem-solving steps. These errors may stem from mis-generalization, where existing concepts are applied inappropriately to new contexts (Andriani & Nurhasanah, 2021). For instance, the study found that PPSTs struggled to grasp fundamental principles and often needed to improve their application. This led to incorrect formula use, mishandling of mathematical steps, and flawed calculations. Such procedural shortcomings may result in incorrect predictions of electromagnetic forces or fields, as evidenced in earlier studies (Gülçiçek & Damlı, 2018).

Similarly, difficulties were noted in PPSTs' understanding of magnetic force on curved wire segments. While successfully computed forces for linear segments, they needed help integrating force contributions over semicircular paths. This procedural gap reveals an incomplete application of the Lorentz force law and Biot-Savart Law, particularly for non-linear geometries. Such findings resonate with studies documenting widespread misconceptions about vector fields, forces, and mathematical principles in electromagnetism (Assem et al., 2024; Mbonyiryivuze et al., 2019). The abstract nature of electromagnetic concepts, compounded by their mathematical rigour, further exacerbates these challenges. Garduza et al. (2023) have emphasised students' struggles in bridging theoretical knowledge with practical applications, particularly in electrostatics, while Rahmawati (2023) have identified the abstractness of these concepts as a key barrier. These findings underscore the need for instructional strategies that address conceptual clarity and procedural competence in electricity and magnetism.

The study further found that PPSTs struggled with foundational principles such as distinguishing fields from forces when addressing unfamiliar electric and magnetic phenomena, which aligns with prior studies. Specifically, difficulties in applying Gauss's and Ampere's laws have been widely documented. These include confusion between electric field and flux (Guisasola et al., 2008; Li & Singh, 2018a; Pepper et al., 2012), magnetic field and circulation (Bozzo et al., 2022; Guisasola et al., 2010), and the misapplication of the superposition principle by assuming only enclosed field sources contribute to the field (Li & Singh, 2018b; Pepper et al., 2012). These conceptual difficulties become pronounced in scenarios such as calculating magnetic forces in multi-wire setups. For instance, PPST52 demonstrates an inability to correctly apply the superposition principle despite determining the current directions accurately. This suggests a limited understanding of the vector nature of forces in systems involving multiple wires and magnetic fields. Such misconceptions indicate the need for targeted interventions to strengthen foundational skills, including vector calculus and field integration.

An analysis of the complexity of test items, aligned with Bloom's Taxonomy, reveals significant cognitive demands in solving and teaching physics concepts like electrostatic force, electric field intensity, and magnetic forces. Studies by Aprianti (2024) and Carpendale and Cooper (2021) advocate for an instructional focus on active engagement and conceptual clarity to bridge these gaps, emphasizing the critical nature of the issue.

Nonetheless, the findings further highlight the importance of higher-order cognitive skills as categorized by Bloom's Taxonomy and its application in complex, multi-conceptual problems which require PPSTs to operate at the *analysis* and *evaluation* levels, emphasizing the need for targeted interventions that build conceptual and procedural knowledge as advocated by De Jong and Ferguson-Hessler (1996). This study contributes to the discourse on enhancing the pedagogy of electricity and magnetism.

Conclusions and Implications

This study has revealed critical insights into common errors and conceptual, procedural and situational difficulties among PPSTs. The findings indicate that many PPSTs struggle with fundamental principles such as the

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relationship between electric and magnetic fields, applying Faraday's Law of Induction, and conceptualising forces in electromagnetic systems. These errors are often rooted in incomplete understanding, rote learning, and a lack of integration between theoretical knowledge and practical application, indicative of more profound conceptual difficulties. These errors can stem from various sources, including inadequate foundational knowledge, misconceptions formed during prior learning experiences, and the challenges of applying theoretical concepts to practical situations.

While transitioning from point charges to dispersed systems, the PPSTs made procedural and situational errors in their understanding of electricity and magnetism. Instead of understanding the charges as regional, the PPSTs treated them as point charges. This implies that distributed charge systems are not appropriately analysed by integrating line charge densities over the spatial region. This implies that PPSTs had difficulty in analysing problems and struggled to use calculus-based methods to solve continuous charge system problems. This necessitates the integration of an experiential learning methodology in the instruction of introductory physics to enhance students' conceptual understanding and critical thinking skills.

While conceptual knowledge influences procedural knowledge, the reverse relationship is also observed, indicating a bidirectional influence between the two. This iterative process of development is facilitated by improved problem representation, which aids in bridging the gap between conceptual understanding and procedural skills. Hence, a need to actively engage students in physics courses by focusing on conceptual, procedural, and situational knowledge to contribute to long-term knowledge retention. Therefore, in teaching physics, researchers recommend emphasizing conceptual knowledge over mathematical knowledge to enhance students' understanding. By focusing on conceptual understanding, teachers can support students in developing deep knowledge of physical phenomena.

The implications of these findings are significant for teacher education programs, highlighting the need for targeted interventions that address these errors or misconceptions. By integrating more comprehensive instructional strategies focusing on conceptual understanding, teacher educators can better prepare PPSTs to teach complex physics concepts effectively. Furthermore, the findings suggest that teacher educators should prioritize integrating inquiry-based learning approaches in their curricula. Such pedagogical strategies enhance content knowledge and equip future teachers with the skills necessary to facilitate student learning effectively.

In light of these implications, future research should explore the effectiveness of specific instructional interventions to address the identified errors or misconceptions. In addition, longitudinal studies could provide valuable insights into how targeted teaching strategies could influence students' conceptual understanding over time. Furthermore, expanding the scope of the study to include both high school students and undergraduate students in mainstream science could further enrich the findings and enhance the generalizability of the results.

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Declaration of Interest

The authors declare no competing interest.

References

Alihodžić, A., Mujezinović, A., & Turajlić, E. (2021). Electric and magnetic field estimation under overhead transmission lines using artificial neural networks. *IEEE Access, 9*, 105876-105891. https://doi.org/10.1109/access.2021.3099760

Anderson, O. R., Randle, D., & Covotsos, T. (2001). The role of ideational networks in laboratory inquiry learning and knowledge of evolution among seventh-grade students. *Science Education, 85*(4), 410 – 425. https://doi.org/10.1002/sce.1016

Andriani, S., Triyanto, .., & Nurhasanah, F. (2021). Procedural error of XIIth grade high school students in solving algebra problems based on Elbrink's theory. *Journal of Physics: Conference Series, 1796*(1), Article 012048. https://doi.org/10.1088/1742-6596/1796/1/012048

Aprianti, S. N. (2024). Computational Thinking-Based Calculus E-Module to Improve Students' Mathematical Literacy Skills. *Strata Social and Humanities Studies*, *2*(2), 135-148.

Assem, H. D., Owusu, M., Issah, S., & Issah, B. (2024). Identifying and dispelling students' misconceptions about electricity and magnetism using inquiry-based learning in selected junior high schools. *ASEAN Journal for Science Education*, *3*(1), 13 – 32.

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Boateng, S., & Mushayikwa, E. (2022). Teaching electricity and magnetism to high school physical science learners: the effectiveness of learning style-based instructions. *PONTE International Scientific Research Journal, 78*(3). https://doi.org/10.21506/j.ponte.2022.3.1

Bollen, L., Kampen, P. V., Baily, C., & Cock, M. D. (2016). Qualitative investigation into students' use of divergence and curl in electromagnetism. *Physical Review Physics Education Research, 12*(2). Article 020134. https://doi.org/10.1103/physrevphyseducres

Bollen, L., Kampen, P. V., & Cock, M. D. (2018). Development, implementation, and assessment of a guided-inquiry teaching-learning sequence on vector calculus in electrodynamics. *Physical Review Physics Education Research, 14*(2). Article 020115. https://doi.org/10.1103/physrevphyseducres

Bozzo, G., Michelini, M., Bonanno, A., & Stefanel, A. (2022). Atwood's Machine and Electromagnetic Induction: A Real Quantitative Experiment to Analyze Students' Ways of Reasoning. *EURASIA Journal of Mathematics, Science and Technology Education*, *18*(2), Article em2077. https://doi.org/10.29333/ejmste/13273

Bruns, J., Gasteiger, H., & Strahl, C. (2021). Conceptualising and measuring domain-specific content knowledge of early childhood educators: a systematic review. *Review of Education, 9(*2), 500-538. https://doi.org/10.1002/rev3.3255

Carpendale, J., & Cooper, R. (2021). Conceptual understanding procedure to elicit metacognition with pre-service physics teachers. *Physics Education*, *56*(2), Article 025008. https://doi.org/10.1088/1361-6552/abc8fd

Çermik, H. (2020). From the Perspectives of High School Students: Difficulties in the Process of Learning Physics. *International Journal of Eurasian Education and Culture*, *5*(9), 793–822. https://doi.org/10.35826/ijoecc.144

Chi, M. T. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are *robust*. *The Journal of the Learning Sciences, 14*(2), 161–199. https://doi.org/10.1207/s15327809jls1402_1

Chi, M. T. (2013). Two kinds and four sub-types of misconceived knowledge, ways to change it, and the learning outcomes. *Psychology of Learning and Motivation*, *58*, 61–82.

Choi, Y. D., & Yun, H. (2019). Visualizing electromagnetic vector fields in matter using mathematica. *Applied Science and Convergence Technology, 28*(3), 66–78. https://doi.org/10.5757/asct.2019.28.3.66

Çoştu, B., Ayas, A., & Níaz, M. (2011). Investigating the effectiveness of a poe-based teaching activity on students' understanding of condensation. *Instructional Science, 40*(1), 47–67. https://doi.org/10.1007/s11251-011-9169-2

Creswell, J. W. (2013). *Qualitative inquiry and research design: Choosing among five approaches* (3rd ed.). Sage.

De Jong, T., & Ferguson-Hessler, M. G. (1996). Types and qualities of knowledge. *Educational Psychologist*, *31*(2), 105–113. https://doi.org/10.1207/s15326985ep3102_2

DiSessa, A.A. (1988). *Knowledge in pieces*. In G. Forman & P. Pufal (Eds), *Constructivism in the computer age* (pp 49–70). Lawrence Erlbaum Associates.

Dori, Y. J., & Belcher, J. W. (2005). Learning electromagnetism with visualizations and active learning. *Visualization in Science Education*, 187–216. https://doi.org/10.1007/1-4020-3613-2_11

Duit, R. (2014). Teaching and learning the physics energy concept. *Teaching and Learning of Energy in K – 12 Education*, 67–85. https://doi.org/10.1007/978-3-319-05017-1_5

Duit, R. & Treagust, D. F. (2011). How can conceptual change contribute to theory and practice in science education?. *Second International Handbook of Science Education,* 107–118. https://doi.org/10.1007/978-1-4020-9041-7_9

Ebenezer, J., Chacko, S., Kaya, O., Koya, S. K., & Ebenezer, D. L. (2009). The effects of common knowledge construction model sequence of lessons on science achievement and relational conceptual change. *Journal of Research in Science Teaching, 47*(1), 25 – 46. https://doi.org/10.1002/tea.20295

Fauskanger, J. & Bjuland, R. (2018). Deep learning as constructed in mathematics teachers' written discourses. *International Electronic Journal of Mathematics Education, 13*(3). https://doi.org/10.12973/iejme/2705

Furió, C., & Guisasola, J. (1998). Difficulties in learning the concept of electrical field. *Science Education*, *82* (4), 511–526.

Garduza, F. A. L., Díaz, M. H. R., & Rosetti, L. G. C. (2023). Engineering Professors' Conceptions on the Conceptual Field of Electrostatics in Mexico. *International Journal of Innovation in Science and Mathematics Education*, *31*(6). https://doi.org/10.30722/ijisme.31.06.003

Griffiths, D. J. (2017). *Introduction to Electrodynamics* (4th ed.). Cambridge University Press

Guisasola, J. (2014). How physics education research contributes to designing teaching sequences. *Springer Proceedings in Physics*, 397–406. https://doi.org/10.1007/978-3-319-00297-2_39

Guisasola, J., Almudí, J. M., Salinas, J., Zuza, K., & Ceberio, M. (2008). The Gauss and Ampere laws: different laws but similar difficulties for student learning. *European Journal of Physics*, *29*(5), 1005.https://doi.org/10.1088/0143-0807/29/5/013

Guisasola, J., Zubimendi, J. L., & Zuza, K. (2010). How much have students learned? research-based teaching on electrical capacitance. *Physical Review Special Topics - Physics Education Research, 6*(2). https://doi.org/10.1103/physrevstper.6.020102.

Gülçiçek, Ç., & Damlı, V. (2018). Analysis of the behaviour of charged particles in electrical and magnetic fields by prospective physics teachers. *European Journal of Physics, 39*(6), Article 065701. https://doi.org/10.1088/1361-6404/aaddd4

Gürel, D. K., Eryılmaz, A., & McDermott, L. C. (2015). A review and comparison of diagnostic instruments to identify students' misconceptions in science. *EURASIA Journal of Mathematics, Science and Technology Education, 11*(5). https://doi.org/10.12973/eurasia.2015.1369a

Hammer, D. (1996). Misconceptions or p-prims: how may alternative perspectives of cognitive structure influence instructional perceptions and intentions. *Journal of the Learning Sciences, 5*(2), 97–127. https://doi.org/10.1207/s15327809jls0502_1

Heckler, A. F., & Sayre, E. C. (2010). What happens between pre- and post-tests: multiple measurements of student understanding during an introductory physics course. *American Journal of Physics, 78*(7), 768-777. https://doi.org/10.1119/1.3384261

Herholdt, R., & Sapire, I. (2014). An error analysis in the early grades of mathematics: A learning opportunity? *South African Journal of Childhood Education*, *4*(1), 43-60.https://doi.org/10.4102/sajce.v4i1.46

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Hernandez, E., Campos, E., Barniol, P., & Zavala, G. (2023). Students' conceptual understanding of electric flux and magnetic circulation. *Physical Review Physics Education Research*, *19*(1), Article 013102. https://doi.org/10.1103/physrevphyseducres.19.013102

Hoyer, C., & Girwidz, R. (2024). Vector representations and unit vector representations of fields: problems of understanding and possible teaching strategies. *Physical Review Physics Education Research, 20*(1). Article 010150 https://doi.org/10.1103/physrevphyseducres.20.010150

Lattery, M. J. (2016). *Deep Learning in Introductory Physics: Exploratory Studies of Model-Based Reasoning*. IAP.

Leniz, A., Zuza, K., & Guisasola, J. (2017). Students' reasoning when tackling electric field and potential in explanation of dc resistive circuits. *Physical Review Physics Education Research, 13*(1). Article 010128. https://doi.org/10.1103/physrevphyseducres

Li, J. & Singh, C. (2018). Investigating and improving introductory physics students' understanding of electric flux. *European Journal of Physics, 39(*4), Article 045711. https://doi.org/10.1088/1361-6404/aabeeb

Listiono, A. E., Tukiman, T., & Dilisti, D. (2025). Analysis Of The Quality Of Learning Achieved Through The Application Of The Inquiry Base Learning Model And Its Effect On Student Learning Interest In Science Laboratory Management And Engineering Subjects. *Journal of Multidisciplinary Research*, *1*(2), 85-92. https://doi.org/10.70963/jmr.v1i2.137

Liu, T., & Sun, H. (2021). Key Competencies of Physics Teachers. *Higher Education Studies, 11*(1), 28–33. https://doi.org/10.5539/hes.v11n1p28

Malgieri, M., Calcagnile, S., Zuccarini, G., & Onorato, P. (2021). High school student difficulties in drawing the field lines for two magnets. *Physics Education, 56*(6), Article 065007. https://doi.org/10.1088/1361-6552/ac1a06

Maloney, D. P. (1985). Rule-governed approaches to physics: conservation of mechanical energy. *Journal of Research in Science Teaching, 22*(3), 261 – 278. https://doi.org/10.1002/tea.3660220308

Maloney, D. P., O'Kuma, T. L., Hieggelke, C. J., & Van Heuvelen, A. (2021). Surveying students' conceptual knowledge of electricity and magnetism. *American Journal of Physics, 89*(9), 757–771.https://doi.org/10.1002/tea.3660220308

Maries, A., Brundage, M. J., & Singh, C. (2022). Using the conceptual survey of electricity and magnetism to investigate progression in student understanding from introductory to advanced levels. *Physical Review Physics Education Research, 18(*2). Article 020114 https://doi.org/10.1103/physrevphyseducres.18.020114

Mbonyiryivuze, A., Yadav, L. L., & Amadalo, M. M. (2019). Students' conceptual understanding of electricity and magnetism and its implications: a review. *African Journal of Educational Studies in Mathematics and Sciences, 15*(2), 55 – 67. https://doi.org/10.4314/ajesms.v15i2.5

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Sage.

Mulhall, P., McKittrick, B., & Gunstone, R. (2001). A perspective on the resolution of confusions in the teaching of electricity. *Research in Science Education*, *31*(4), 575-587.https://doi.org/10.1023/a:1013154125379

Ng, Y. F., Chan, K. K., Lei, H., Mok, p., & Leung, S. (2019). Pedagogy and innovation in science education: a case study of an experiential learning science undergraduate course. *The European Journal of Social &Amp; Behavioural Sciences, 25*(2), 156–173. https://doi.org/10.15405/ejsbs.254

Nousiainen, M. (2012). Making concept maps useful for physics teacher education: Analysis of epistemic content of links. *Journal of Baltic Science Education*, *11*(1), 29–42. https://doi.org/10.33225/jbse/12.11.29

Novotná, S., & Demkanin, P. (2024). Physics teachers and use of sensors by pupils themselves, preliminary ideas of typology of physics teachers. *Journal of Physics: Conference Series, 2750*(1), Article 012042. https://doi.org/10.1088/1742-6596/2750/1/012042

Pepper, R. E., Chasteen, S. V., Pollock, S. J., & Perkins, K. K. (2012). Observations on student difficulties with mathematics in upper-division electricity and magnetism. *Physical Review Special Topics - Physics Education Research, 8*(1). https://doi.org/10.1103/physrevstper.8.010111

Pherson-Geyser, G. M., Villiers, R. D., & Kavai, P. (2020). The use of experiential learning as a teaching strategy in life sciences. *International Journal of Instruction, 13*(3), 877–894. https://doi.org/10.29333/iji.2020.13358a

Qin, W., Cheng, M., Wang, J., Zhu, X., Wang, Z., & Hua, W. (2023). Compatibility analysis among vector magnetic circuit theory, electrical circuit theory, and electromagnetic field theory. *IEEE Access, 11*, 113008-113016. https://doi.org/10.1109/access.2023.3323407

Rahmawati, R., Widiasih, W., Marisda, D. H., & Riskawati, R. (2023). Using four-tier test to identify prospective elementary teacher students' misconception on electricity topic. *Jurnal Penelitian Pendidikan IPA, 9*(10), 7793-7802. https://doi.org/10.29303/jppipa.v9i10.3272

Rittle-Johnson, B., & Alibali, M. W. (1999). Conceptual and procedural knowledge of mathematics: does one lead to the other?. *Journal of Educational Psychology, 91*(1), 175–189. https://doi.org/10.1037/0022-0663.91.1.175

Rittle-Johnson, B., Siegler, R. S., & Alibali, M. W. (2001). Developing conceptual understanding and procedural skill in mathematics: an iterative process. *Journal of Educational Psychology, 93*(2), 346 – 362. https://doi.org/10.1037/0022-0663.93.2.346

Safkolam, R., Madahae, S., & Saleah, P. (2024). The effects of inquiry-based learning activities to understand the nature of science of science student teachers. *International Journal of Instruction*, *17*(1), 479–496.https://doi.org/10.29333/iji.2024.17125a

Sangam, D., & Jesiek, B. K. (2012). Conceptual understanding of resistive electric circuits among first-year engineering students. *ASEE Annual Conference &Amp Exposition Proceedings.* https://doi.org/10.18260/1-2--21097

Sapriati, A., Rahayu, U., Sausan, I., & Sekarwinahyu, M. (2024). The impact of inquiry-based learning on students' critical thinking in biology education programs within open and distance learning systems. *Jurnal Pendidikan IPA Indonesia*, *13*(3). https://doi.org/10.15294/7sty9026

Shavelson, R. J., Phillips, D. C., Towne, L., & Feuer, M. J. (2003). On the science of education design studies. *Educational Researcher, 32(*1), 25 – 28. https://doi.org/10.3102/0013189x032001025

Siyepu, S. (2013). The zone of proximal development in the learning of mathematics. *South African Journal of Education*, *33*(2), 1–13.https://hdl.handle.net/10520/EJC134983

Smith, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3*(2), 115–163. https://doi.org/10.1207/s15327809jls0302_1

Suárez, Á., Marti, A. C., Zuza, K., & Guisasola, J. (2024). Learning difficulties among students when applying ampére-maxwell's law and its implications for teaching. *Physical Review Physics Education Research, 20*(1). https://doi.org/10.1103/physrevphyseducres.20.010143

Turgut, Ü., Gürbüz, F., & Turgut, G. (2011). An investigation 10th grade students' misconceptions about electric current. *Procedia-Social and Behavioral Sciences*, *15*, 1965–1971. https://doi.org/10.1016/j.sbspro.2011.04.036

Vuola, K., & Nousiainen, M. (2020). Physics knowledge justification: an analysis framework to examine physics content knowledge. *Nordina: Nordic studies in science education*, *16*(2), 149–166. https://doi.org/10.5617/nordina.6916

Wallace, C. S. & Chasteen, S. V. (2010). Upper-division students' difficulties with ampère's law. *Physical Review Special Topics - Physics Education Research, 6*(2). Article 020115 https://doi.org/10.1103/physrevstper.6.020115

Wilcox, B. R., Pollock, S. J., & Bolton, D. (2020). Retention of conceptual learning after an interactive introductory mechanics course. *Physical Review Physics Education Research, 16*(1). Article 010140. https://doi.org/10.1103/physrevphyseducres.16.010140

Yin, R. K. (2018). *Case study research and applications*. Sage Publication.

Zuza, K., Kampen, P. V., Cock, M. D., Kelly, T., & Guisasola, J. (2018). Introductory university physics students' understanding of some key characteristics of classical theory of the electromagnetic field. *Physical Review Physics Education Research, 14*(2). Article: 020117 https://doi.org/10.1103/physrevphyseducres

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